

# Fermi-Bose quantum degenerate $^{40}\text{K}$ - $^{87}\text{Rb}$ mixture with attractive interaction

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We report on the achievement of simultaneous quantum degeneracy in a mixed gas of fermionic  $^{40}\text{K}$  and bosonic  $^{87}\text{Rb}$ . Potassium is cooled to 0.3 times the Fermi temperature by means of an efficient thermalization with evaporatively cooled rubidium. Direct measurement of the collisional cross-section confirms a large interspecies attraction. This interaction is shown to affect the expansion of the Bose-Einstein condensate released from the magnetic trap, where it is immersed in the Fermi sea.

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The recently demonstrated quantum degeneracy of Fermi-Bose (FB) mixtures of dilute atomic gases [1, 2, 3] promises to further enrich the field of the physics of degenerate matter at ultralow temperatures [4, 5]. When a Bose-Einstein condensate (BEC) interacts with a Fermi gas, novel phenomena are expected to occur. The most appealing one is certainly BCS-like fermionic superfluidity, since a BEC could affect interactions between fermions [6, 7]. Furthermore, different FB interaction regimes could allow studies of phase-separation [8, 9] or of the stability properties of the binary mixtures [10].

The mixtures so far reported have in common the use of fermionic  $^6\text{Li}$ , combined with a BEC of  $^7\text{Li}$  [1, 2], or of  $^{23}\text{Na}$  [3]. For the  $^6\text{Li}$ - $^7\text{Li}$  mixtures the FB interaction is *repulsive*, with possible consequences for the separation of the components, and eventually for the thermal contact. For the  $^6\text{Li}$ - $^{23}\text{Na}$  case, the interaction has not been measured, however the theoretical predictions are again in favor of a repulsive character [11].

A different, promising scenario would be offered by mixtures combining species with attractive interaction, because the absence of a phase separation would allow efficient cooling well below the Fermi temperature and would favor the interaction between the two components in the degenerate regime. With this respect, a mixture composed of  $^{40}\text{K}$  and  $^{87}\text{Rb}$  would be particularly interesting. Indeed, precise  $^{41}\text{K}$ - $^{87}\text{Rb}$  interspecies collisional studies at ultralow temperatures [12], inferred an *attractive* character for the interaction of the  $^{40}\text{K}$ - $^{87}\text{Rb}$  pair.

In this Letter we report the production of such a novel macroscopic quantum system, in which a degenerate  $^{40}\text{K}$  Fermi gas, composed of more than  $10^4$  atoms, coexists with a  $^{87}\text{Rb}$  Bose-Einstein condensate of up to  $2 \times 10^4$  atoms. The large interspecies scattering length results in an efficient sympathetic cooling of  $^{40}\text{K}$  with evaporatively cooled Rb, as in the case of Bose-Einstein condensation of  $^{41}\text{K}$  [13]. This cooling scheme represents also an alternative to the single-species evaporation approach [14] that was early demonstrated to produce a Fermi gas of K atoms. We observe signatures of the large interaction of the two components also in the degenerate regime.

The degenerate mixture is produced using the apparatus described in Ref. [13]. In brief, about  $10^5$   $^{40}\text{K}$  atoms and  $5 \times 10^8$   $^{87}\text{Rb}$  atoms at a temperature around  $100 \mu\text{K}$  are loaded in an elongated magnetostatic trap using a double magneto-optical trap apparatus. As opposed to the case of  $^{41}\text{K}$  [13], combined magneto-optical trapping of  $^{40}\text{K}$  and  $^{87}\text{Rb}$  is efficient, as was also shown in Ref. [15]. Prior to magnetic trapping, both species are prepared in their doubly polarized spin state,  $|F = 9/2, m_F = 9/2\rangle$  for K and  $|2, 2\rangle$  for Rb. These states experience the same trapping potential, with axial and radial harmonic frequencies  $\omega_a = 2\pi \times 24 \text{ s}^{-1}$  and  $\omega_r = 2\pi \times 317 \text{ s}^{-1}$  for K, while those for Rb are a factor  $(M_{\text{Rb}}/M_{\text{K}})^{1/2} \approx 1.47$  smaller. Evaporative cooling is then performed selectively on the Rb sample. Due to the different gyromagnetic factors of the two species a radio-frequency evaporation scheme could be implemented [16], in contrast to the boson-boson mixture, for which microwave radiation had to be used.

With an evaporation ramp lasting about 25 s we are able to cool typically  $2 \times 10^4$  K atoms and  $10^5$  Rb atoms to below  $1 \mu\text{K}$ . Sympathetic cooling of  $^{40}\text{K}$  with  $^{87}\text{Rb}$  is very efficient, with a large ratio of "good" elastic collisions to "bad" inelastic collisions. We have measured the interspecies scattering cross-section by performing a rethermalization measurement at a temperature around  $400 \text{ nK}$ , at which both species are still non-degenerate gases. We drive the mixture out of equilibrium with a short, Rb-selective, parametric heating phase [12], and we observe the subsequent heating of K, which is mediated by elastic interspecies collisions. For a K sample composed by  $1.2 \times 10^4$  atoms, coexisting with  $4 \times 10^4$  Rb atoms we measure a short thermalization time  $\tau = 57(20) \text{ ms}$ . At these ultralow temperatures the collisions have almost exclusively a *s*-wave character and, following the model discussed in [12]  $\tau$  is linked to the scattering length  $a$  through  $\tau^{-1} = 4\pi a^2 \xi \bar{n} v / \alpha_s$ , where  $\bar{n} = (\frac{1}{N_{\text{K}}} + \frac{1}{N_{\text{Rb}}}) \int n_{\text{K}} n_{\text{Rb}} d^3x$  is the effective density of K and

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Rb atoms,  $v$  is their relative velocity,  $\xi \approx 0.86$  is a factor which takes into account the different mass of two colliding atoms, and  $\alpha_s \approx 2.7$  is the average number of collisions needed for thermalization. Even though K atoms cannot thermalize between themselves, since  $s$ -wave collisions are forbidden for identical fermions, the thermalization with Rb happens on a timescale longer than the mean period of oscillation in the trap, and this ensures thermalization of the K sample. Actually we have observed that both the density and momentum distributions have gaussian profiles that lead to the same temperature. From the measured  $\tau$  we derive a quite large magnitude for the  $^{40}\text{K}$ - $^{87}\text{Rb}$  scattering length:  $|a| = 330^{+160}_{-100} a_0$ . Here the uncertainty is dominated by that on  $\tau$  and by a 40% uncertainty on the atom number. The direct measurement with the fermionic isotope is in agreement with the value  $a = -261^{+170}_{-159} a_0$  that we previously inferred by mass-scaling from collisional measurements on the bosonic  $^{41}\text{K}$ - $^{87}\text{Rb}$  mixture [12]. The measurement of a large value for  $|a|$  also confirms the *attractive* character of the interaction, since a positive scattering length would have been compatible only with a much smaller magnitude [13].

By further cooling the mixture we have evidence of the formation of a degenerate Fermi gas coexisting with a Bose-Einstein condensate. In Fig. 1 we show a series of absorption images of the mixture for three different final energies of the evaporation ramp, which reveals the different nature of the two degenerate gases. Both samples are imaged in the same experimental run, by using two short, delayed light pulses. The images are taken after a ballistic expansion appropriate to measure the momentum distribution of the samples; in particular the expansion lasts 4.5 ms for K and 17.5 ms for Rb. Sections of such images are also shown: they are taken along the vertical direction for K, and along the horizontal direction for Rb. With our experimental parameters, we have a Fermi temperature  $T_F = 250$  nK and a critical temperature for BEC  $T_c = 110$  nK for a sample composed of  $10^4$  and  $2 \times 10^4$  atoms, respectively.

Thermometry of the system is provided by the bosonic component, assuming thermal equilibrium between the two components. As the temperature is decreased by almost a factor of two (from top to bottom in Fig. 1), Rb undergoes the phase-transition to BEC, while the width of the fermionic component remains almost constant. A fit of the coldest K cloud with a Thomas-Fermi profile [17] gives a radius  $R = 52 \mu\text{m}$ , which is consistent to within 10% with the minimum radius allowed by Fermi statistics:  $R = R_F \sqrt{1 + \omega_r^2 \tau^2}$ , where  $R_F = \sqrt{2k_B T_F / (M \omega_r^2)}$  is the Fermi radius and  $\tau$  is the expansion time. For the *quasi-pure* BEC shown in Fig. 1, a fit to both the thermal and condensate components with gaussian profiles indicate a condensate fraction of 60%. This implies a temperature  $T = 80$  nK of both the BEC and the Fermi gas, which corresponds to  $0.3 T_F$ .

In these conditions, we see a small decrease of the number of K atoms on the timescale of 1 s, which is the lifetime of the BEC in our system. This indicates the presence of some kind of inelastic collisional process, which will be the object of future investigation.

Further evidence for the achievement of quantum degeneracy is obtained by studying the gaussian  $1/e$  width of the fermionic sample as a function of temperature. As shown in Fig. 2 the square of the width, normalized to  $R_F$ , scales linearly for  $T > T_F$ , indicating thermal equilibrium between K and Rb. Below  $T_F$ , the data deviate from the behavior expected for a classical gas, and indeed they are better reproduced by the prediction of the model for an ideal Fermi gas [17].

Since we have also observed degenerate mixtures in which the thermal fraction of the condensate was below our detection limit of nearly 30%, the attainment of temperatures lower than those reported cannot be excluded. However, boson thermometry is no longer possible in this regime, and different techniques would be necessary to investigate the evolution of sympathetic cooling when both species are well below their critical temperatures.

In the present experiment we have an evidence for thermal contact between the two species in the degenerate regime, even when no thermal component is detectable for the Rb BEC. This is obtained by leaving the degenerate mixture in the magnetic trap for a relatively long time after the end of the evaporation. The Rb temperature is kept constant by means of a radio-frequency shield, but the background heating ( $\approx 100$  nK/s) caused by fluctuations in the magnetic field, continuously removes atoms from the BEC. This is illustrated in Fig. 3, together with the simultaneous behavior of K. The evolution of the width of the fermionic distribution indicates that K starts to heat up only when Rb is almost completely evaporated from the trap. Although the gaussian width is not a sensitive "thermometer" at low temperatures, as shown in Fig. 2, the results reported in Fig. 3 are significant. Indeed, if K were thermally decoupled from Rb, its heating at the observed rate would be detectable after 1 s even in the extreme case of a starting temperature  $T \ll T_F$ .

However, it is difficult to determine whether the thermal contact is direct or mediated by a possible, undetected thermal cloud. In our magnetic trap, the centers of mass of the two species are displaced due to the different gravitational sag for K and Rb. This displacement,  $\Delta z = 2.9 \mu\text{m}$ , is not sufficiently large to affect the geometrical overlap of the two degenerate components, since the radial sizes of the Fermi and Bose gases are  $R_F = 5.1 \mu\text{m}$  and  $R_B = 2 \mu\text{m}$ , respectively. Therefore, the BEC is completely immersed in the Fermi sea, with a ratio of the two volumes of approximately 1:16, hence direct thermal exchange is possible. However, the contribution of an undetected thermal cloud cannot be excluded, also because of the large K-Rb interaction. For instance at  $T = 0.5 T_F$  we calculate that  $10^4$  uncondensed bosons would thermalize with an equal number of fermions in about 50 ms.

The large attractive interspecies interaction is expected to affect the density profile of both degenerate gases [10, 18].

Our experimental configuration is more suitable for the observation of the effect of the mutual interaction on the boson. While the Rb BEC is completely immersed in the Fermi sea, only a relatively small volume fraction of K is exposed to the attraction. In fact, we have seen a modification on the ballistic expansion of the BEC due to the presence of the other species. In general, we found that BECs coexisting with the Fermi gas invert their aspect ratio more rapidly than normal during the expansion. As an example, the evolution of the axial-to-radial aspect ratio of the condensate is shown in Fig. 4 for both the cases of a pure BEC and of a BEC with the Fermi gas. In the former case the expansion is in agreement with the theoretical prediction [19] for the experimental trap parameters. The latter case is instead better reproduced by the behavior expected for a pure BEC confined in an effective potential with frequencies 10% larger than the actual ones. This constitutes a direct evidence of the interaction, and qualitatively agrees with the expectations reported in Ref. [18] of a tighter confinement for a BEC in a Fermi gas with mutual attraction. However, a precise reconstruction of the BEC density profile in the trap is not straightforward from these observations. Indeed, in modelling the data of Fig. 4 as appropriate for a free-expanding condensate we have neglected possible effects of the interaction of Rb with K also during the early phases of the expansion, which instead cannot be ruled out a priori and need further investigation.

In conclusion we have produced a degenerate mixture in which a Rb BEC is fully immersed in a K Fermi sea. The mutual attractive interaction constitutes an important novelty, since it allows thermal contact between the FB components to continue into the degenerate regime, where loss-induced heating of the Fermi gas may also play a significant role [20]. A deeper exploration of thermal exchange in the degenerate regime will require the development of new techniques for better thermometry. One possible scheme could be based on the production of velocity-selected Rb atoms [21] for the study of their collisional relaxation in the fermionic gas [22]. We also observed a first evidence of the effect of the strong FB interaction on the density profile of the bosons. Further insight in this phenomenology could be obtained, for instance, through the study of the dynamics induced by the interaction, following the release of one of the two species from the trap [23].

Finally, we note that this K-Rb mixture opens new possibilities for the production of ultracold heteronuclear molecules. In particular, as recently discussed in Ref. [24], dipolar fermions could provide a new landscape for the quest of fermionic superfluidity.

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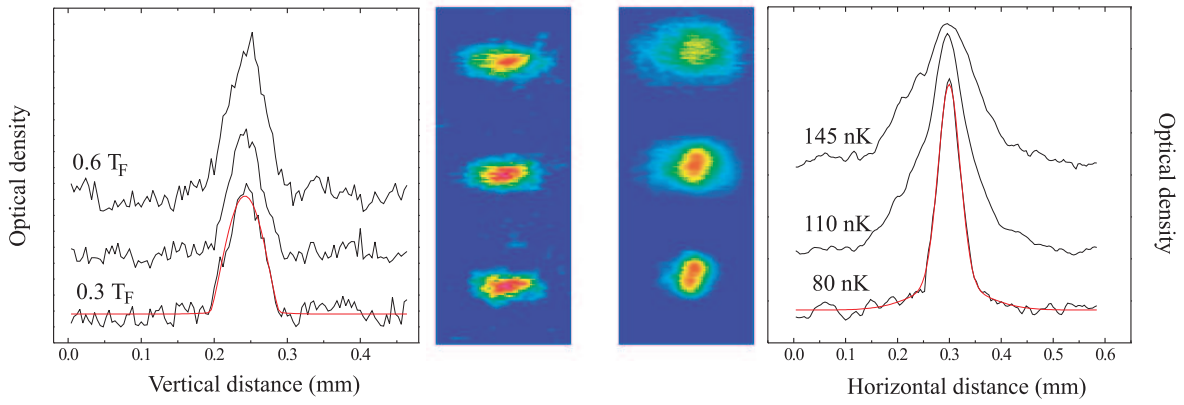


FIG. 1: Simultaneous onset of Fermi degeneracy for  $^{40}\text{K}$  (left) and of Bose-Einstein condensation for  $^{87}\text{Rb}$  (right). The absorption images are taken for three decreasing temperatures, after 4.5 ms of expansion for K and 17.5 ms for Rb, and the sections show the profile of the momentum distributions. The bosons provide a thermometry of the system: in the coldest sample, the Rb BEC has a 40% thermal component, and the temperature is  $T=0.74T_c=80$  nK, which corresponds to  $T=0.3T_F$  for K. The Thomas-Fermi radius of the K profile is  $R=52\text{ }\mu\text{m}$ , consistent with the radius expected for a degenerate Fermi gas.

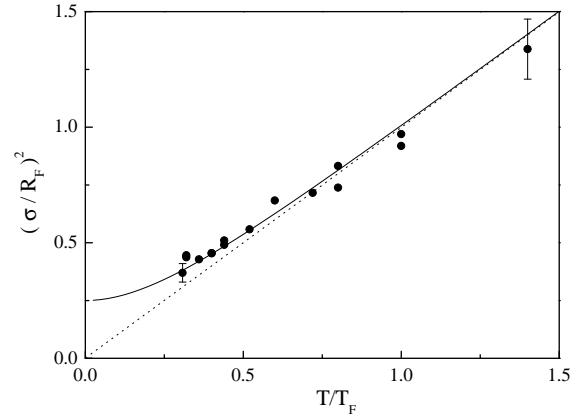


FIG. 2: Gaussian  $1/e$  radius of the radial distribution of K atoms, versus the reduced Fermi temperature. The temperature is given by the Rb sample and  $T_F=250$  nK. The solid line is the theoretical prediction for an ideal Fermi gas, while the dotted line is the classical behavior.

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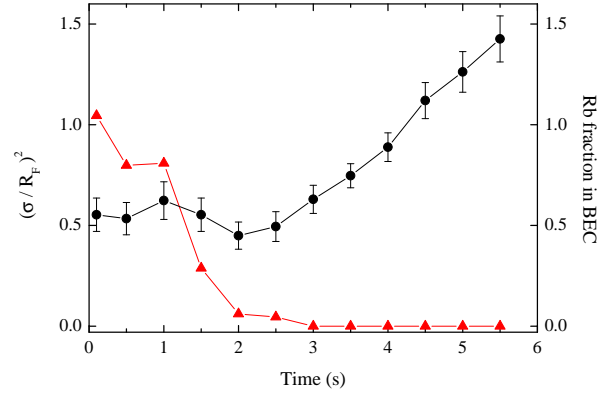


FIG. 3: Thermal exchange between the two degenerate gases. The gaussian width of  $^{40}\text{K}$  (circles) increases only when  $^{87}\text{Rb}$  atoms (triangles) are almost completely evaporated from the trap, as explained in the text. Each data point is the average of three or four measurements, and the solid lines are a guide to the eye.

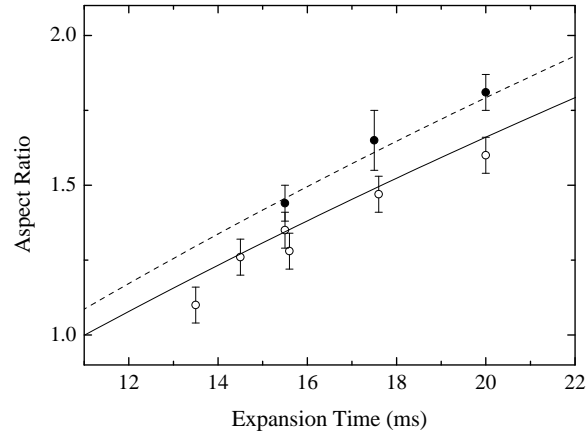


FIG. 4: Modification of the expansion of a Rb BEC due to interaction with the K Fermi gas. The radial-to-axial aspect ratio increases more rapidly with time for condensates created with K (solid circles) than for pure condensates (open circles). The two curves are the theoretical predictions for the expansion of a pure BEC for the trap parameters of the present experiment (solid line) and for trap frequencies 10% larger (dashed line).